# CHAPTER 5

# SETTLEMENT ANALYSES

## 5-1. Settlement problems.

*a.* Significant aspects of the settlement of structures are total settlement-magnitude of downward movements- and differential settlement-difference in settlements at different locations in the structure. Table 5-1 lists conditions that cause settlements which occur during construction and result in only minor problems and postconstruction settlements which occur after a structure is completed or after critical features are completed. Differential settlements distort a structure. A structure can generally tolerate large uniform, or nearly uniform, settlements.

*b.* Differential settlement can have a number of undesirable results:

(1) Tilting is unsightly. A tilt of 1/250 can be distinguished by the unaided eye.

(2) Moderate differential settlement causes cracking and architectural damage. With increasing differential settlement, doors and windows may become distorted and not open and close properly. Larger differential settlements may cause floors and stairways to become uneven and treacherous and windows to shatter. At this point, the usefulness of the building has been seriously impaired.

(3) Severe differential settlements may impair structural integrity and make structures susceptible to collapse during an earthquake or other major vibration.

(4) If a structure settles relative to the surrounding ground, or the ground settles relative to the structure, entryways may be disrupted, and utility lines may be damaged where they enter the structure.

*c.* Even if settlements are uniform or nearly so, large total settlements can also result in problems:

(1) Sites located near a river, lake, or ocean may flood during periods of high water.

(2) Surface drainage may be disrupted. If water ponds around and beneath structures, they may become inaccessible and subject to mildew and wood rot.

*d.* Experience provides a basis for estimating the magnitudes of differential settlement that cause cracking of architectural finishes, such as plaster, stucco, and brick facing. Differential settlement is best expressed as the angular distortion in radians between two points. Angular distortion, which always accompanies settlement of a building, is determined by the uniformity of foundation soils, the stiffness of the structure and its foundation, and the distribution of load within the building. In conventional settlement analyses of the type described in this manual, the stiffness of the building and foundation are not considered. Tolerable angular distortions are listed in table 5-2, and empirical correlations that may be used to estimate probable angular distortions based on calculated maximum settlements are summarized in table 5-3. Because of the natural variability of soils, differential settlement will occur though total settlements are calculated to be uniform. An indirect means for controlling differential settlement is to limit total settlement to 3 inches for structures on clay and to 1 1/2 inches for structures on sand.

## 5-2. Loads causing settlement.

a. Loads causing settlement always include the estimated dead load and a portion or all of the live load. For office buildings, about 50 percent of the estimated building live load may be assumed to cause settlement. For heavily loaded warehouses and similar structures, the full live load should be used.

*b.* For many purposes, settlements need be computed only for the maximum dead load plus settlement-causing live load. Occasionally, settlements occurring during a part of the construction period must be computed. This may require additional stress computations for partial loading conditions.

c. Loads that are less than the preconsolidation stress cause minor settlements because only recompression of soil occurs. The increment of loading that exceeds the preconsolidation stress causes relatively large settlements and occurs along the virgin compression portion of laboratory consolidation curves. A careful estimate of preconsolidation stresses is essential for settlement analyses. Means for estimating such stresses are given in chapter 3.

## 5-3. Stress computations.

a. One of the first steps in a settlement analysis is computation of effective overburden stresses in the soil before and after loading. The initial stress $p_1'$ at any depth is equal to the effective weight of overlying soils and may be determined by multiplying the effective unit weight of the soil by its thickness. It is customary to construct a load-depth diagram by plotting

*Table 5-1. Causes of Settlement*

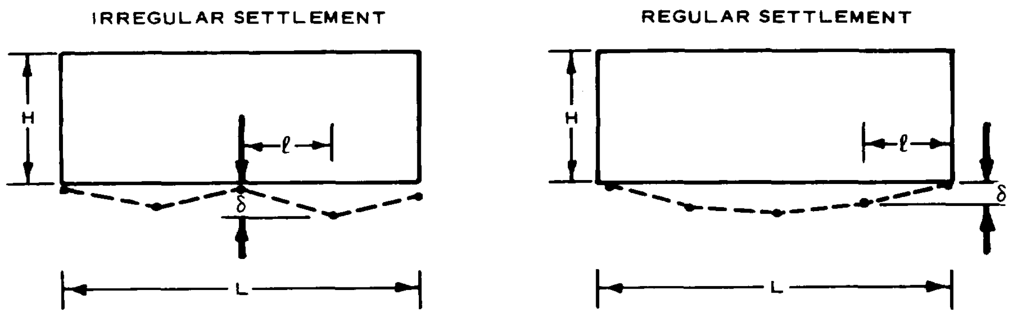
| Cause | Comment |
|---|---|
| Compression of foundation soils under static loads. | Soft, normally consolidated clays and peaty soils are most compressible. Loose silts, sands, and gravels are also quite compressible. |
| Compression of soft clays due to lowering ground-water table. | Increased effective stress causes settlement with no increase in surface load. |
| Compression of cohesionless soils due to vibrations. | Loose sands and gravels are most susceptible.Settlement can be caused by machine vibrations, earthquakes, and blasts. |
| Compression of foundation soil due to wetting. | Loose silty sands and gravels are most susceptible.Settlements can be caused by rise in groundwater table or by infiltration. |
| Shrinkage of cohesive soils caused by drying. | Highly plastic clays are most susceptible.Increase in temperature under buildings containing ovens or furnaces may accelerate drying. Wetting of highly plastic clays can cause swelling and heave of foundations. |
| Loss of foundation support due to erosion. | Waterfront foundations must extend below maximum erosion depth. |
| Loss of foundation support due to excavation of adjacent ground. | Most pronounced in soft, saturated clays. |
| Loss of support due to lateral shifting of the adjacent ground | Lateral shifting may result from landslides, slow downhill creep, or movement of retaining structures. |
| Loss of support due to formation of sinkhole. | Soils overlying cavernous limestone and broken conduits are susceptible. |
| Loss of support due to thawing of permafrost.foundation heat. | Permafrost should be insulated from |
| Loss of support due to partial or complete liquefaction. | Loose, saturated sands are most susceptible. |
| Downdrag on piles driven through soft clay. | Loading on piles is increased by negative skin friction if soil around upper part of pile settles. |

stress versus depth, using average unit moist weights of soil above the water table and average unit submerged weights below the water table.

*b.* The final stress p at any depth is equal to the effective overburden stress after the structure is completed plus the stress resulting from the structure load. If the structure is founded on individual footings, the final stress is the sum of stresses imposed by all footings.

*c.* Foundation stresses caused by applied loads are generally computed assuming the foundation to consist of an elastic, isotropic, homogeneous mass of semiinfinite extent, i.e., the Boussinesq case. The increment of stress at various depths is determined by means of influence values, such as shown in figures 5-1 and 5-2, which give the vertical stress beneath a rectangular area for uniform and triangular distributions of load, respectively. Influence values for vertical

*Table 5-2. Value of Angular Distortion ($\delta/\vartheta$) That Can Be Tolerated Without Cracking*




| Type of Building | L/H | Allowable $\delta/\vartheta$ |
|---|---|---|
| Steel frame with flexible siding | -- | 0.008 |
| Steel or reinforced concrete frame with insensitive finish such as dry wall, glass, or moveable panels | -- | 0.002 to 0.003 |
| Steel or reinforced concrete frame with brick, block, plaster, or stucco finish | $\geq 5$ | 0.002 |
| | $\leq 3$ | 0.001 |
| Load-bearing brick, tile, or concrete block walls | $\geq 5$ | 0.0008 |
| | $\leq 3$ | 0.0004 |
| Circular steel tanks on flexible base, with fixed top | -- | 0.008 |
| Circular steel tanks on flexible base, with floating top | | 0.002 to 0.003 |
| Tall slender structures, such as stacks, silos, and water tanks, with rigid mat foundations | -- | 0.002 |

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stress beneath a circular area are shown in figure 5-3. If the foundation consists of a large number of individual footings, influence charts based on the Boussinesq case will greatly facilitate the computation of stresses. Programs for digital computers and programmable calculators are also available.

*d.* A structure excavation reduces stress in foundation subsoils. The decrease in vertical stresses caused by the weight of excavated material is computed in the manner described in the previous paragraph. The bottom of the excavation is used as a reference; vertical stresses produced by the weight of excavated material are subtracted algebraically from the original overburden pressure to compute final foundation stresses.

**5-4. Settlement of foundations on clay.**

*a.* When a load is applied over a limited area on clay, some settlement occurs immediately. This immediate settlement, $\Delta H_i$, , has two components: that caused by distortion or change of shape of the clay beneath the loaded area, and that caused by immediate volume change in unsaturated soils. In saturated clays, there is little or no immediate volume change because time is required for water to drain from the clay.

*b.* Immediate settlements can be estimated using methods given in chapter 10. Values of undrained modulus determined from the slopes of stress-strain curves from unconsolidated-undrained laboratory compression tests are frequently only one-half or one-third as large as the in situ modulus. This difference is due to disturbance effects, and the disparity may be even more significant if the amount of disturbance is unusually large. The undrained modulus of the clay may be estimated from figure 3-20. The values of the K in this figure were determined from the field measurements and, therefore, are considered to be unaffected by disturbance. The value of Poisson's ratio is equal to 0.5 for saturated clays. For partly saturated clays, a value of 0.3 can be assumed. Because immediate settlements occur as load is applied and are at least partially included in results of laboratory consolidation tests, they are often not computed and only consolidation settlements are considered to affect a structure.

**5-5. Consolidation settlement.** Consolidation settlement of cohesive soil is normally computed from pressure-void ratio relations from laboratory consolidation tests on representative samples. Typical examples of pressure-void ratio curves for insensitive and sensitive, normally loaded clays, and preconsolidated clays are shown in figure 3-7. Excavation results in a rebound of foundation soils and subsequent recompression when structure loads are added. This

*Table 5-3. Empirical Correlations Between Maximum ($\Delta$) and Angular Distortion ($\delta/\vartheta$)*

| Type of Foundation | Approximate Value of $\delta/\vartheta$ for[a] $\Delta$= 1 in. |
|---|---|
| Mats on sand | 1/750(0.0013) |
| Rectangular mats on varved silt | 1/1000 to 1/2000 (0.001 to 0.0005) |
| Square mats on varved silt (0.0005 to 0.0003) | 1/2000 to 1/3000 |
| Mats on clay | 1/1250(0.0008) |
| Spread footings on sand | 1/600(0.0017) |
| Spread footings on varved silt | 1/600(0.0017) |
| Spread footings on clay | 1/1000(0.0010) |

a $\delta/\vartheta$ increases roughly in proportion with $\Delta$. For $\Delta$ = 2 in., values of $\delta/\vartheta$ would be about twice as large as shown, for $\Delta$ = 3 inches, three times as large, etc.

*(Courtesy ofJ. P. Gould and J. D. Parsons, "Long - Term Performance of Tall Buildings of New York City Varied Silts, " Proceedings, International Conference on Planning and Design of Tall Buildings, Lehigh University, Bethlehem, Pa., 1975. Reprinted by permission of American Society of Civil Engineers, New York.)*

sequence should be simulated in consolidation tests by loading the specimen to the existing overburden pressure po, unloading to the estimated stress after excavation $p_{exc}$, and reloading the specimen to define the p-e curve at loads in excess of overburden and preconsolidation stresses. Curves designated $K_u$ in figure 3-7 are laboratory p-e curves. Soil disturbance during sampling affects laboratory p-e curves so that it usually

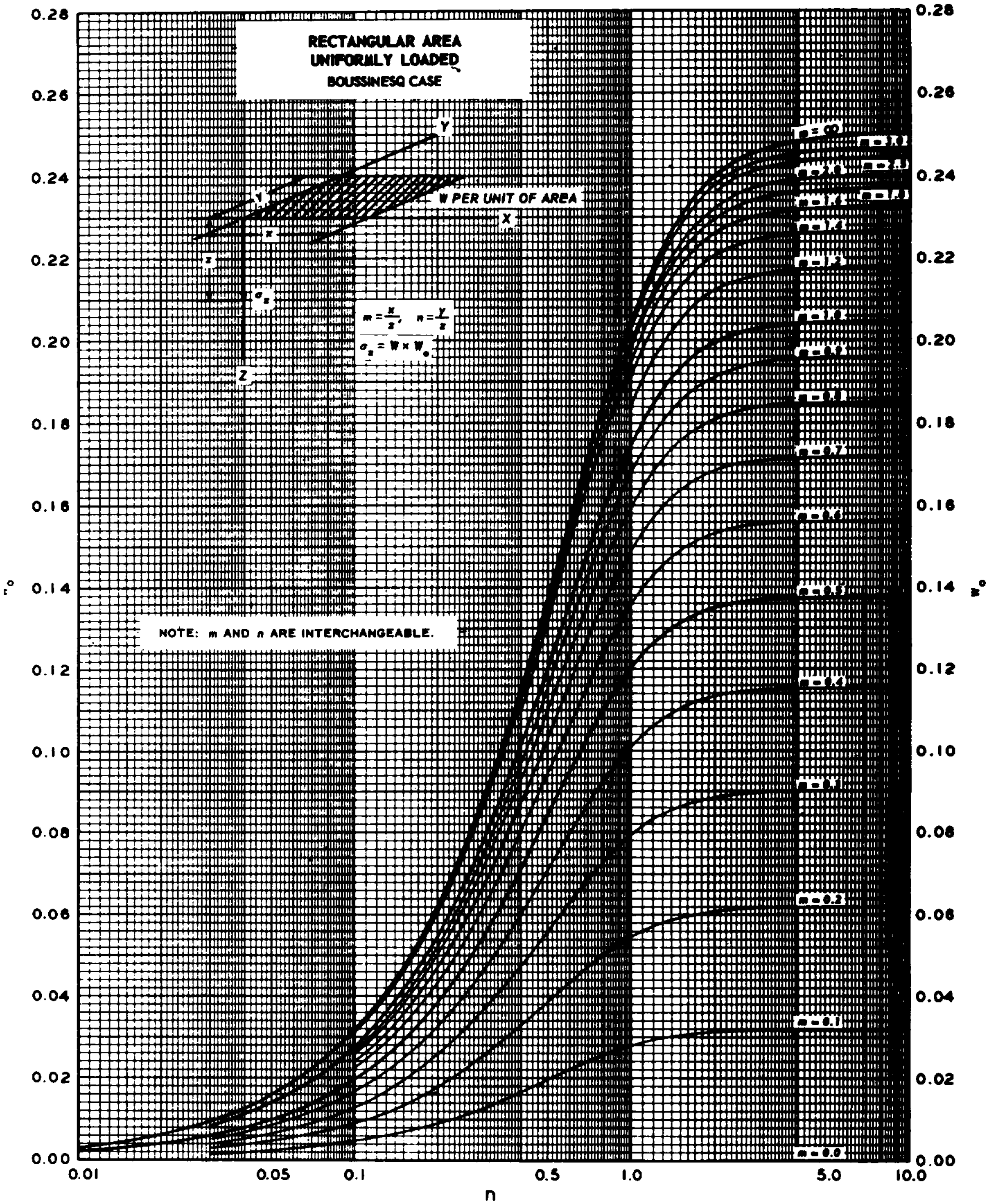


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*Figure 5-1. Vertical stress beneath a uniformly loaded rectangular area.*

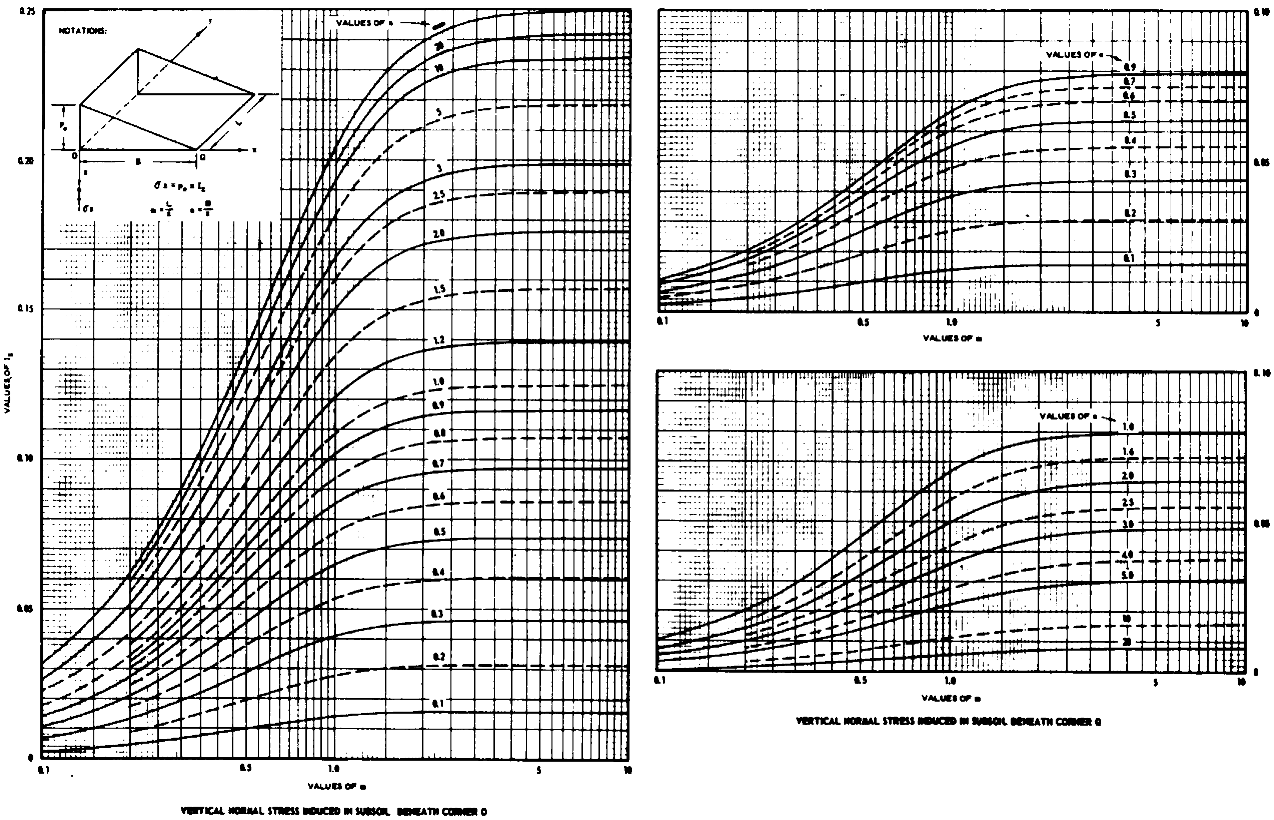


*Figure 5-2. Vertical stress beneath a triangular distribution of load on a rectangular area.*

becomes necessary to construct a field p-e curve simulating consolidation in the field. These constructions are also shown in figure 3-7. They are based on the assumption that the straight lower branch of the field p-e curve, K, intersects the laboratory curve at $e = 0.4e_0$. Furthermore, the field curve must pass through point a, corresponding to the present overburden pressure and the natural void ratio. The field compression index, $C_c$, is taken as the slope of the straight lower branch of K on the semilogarithmic diagram.

*a. Settlement computations.* The total settlement, $\Delta H$, of a foundation stratum is computed according to the following formula:

$$\Delta H = \frac{e_1 - e_2}{1 + e_0} H \qquad (5\text{-}1)$$

where

- $e_1$, $e_2$ = initial and final void ratios, respectively, from the field pressure-void curves, corresponding to the initial and final effective foundation pressures
- eo = average initial void of the stratum
- H = total thickness of the compressible stratum This formula also may be used to estimate foundation rebound due to excavation. When the lower portion of

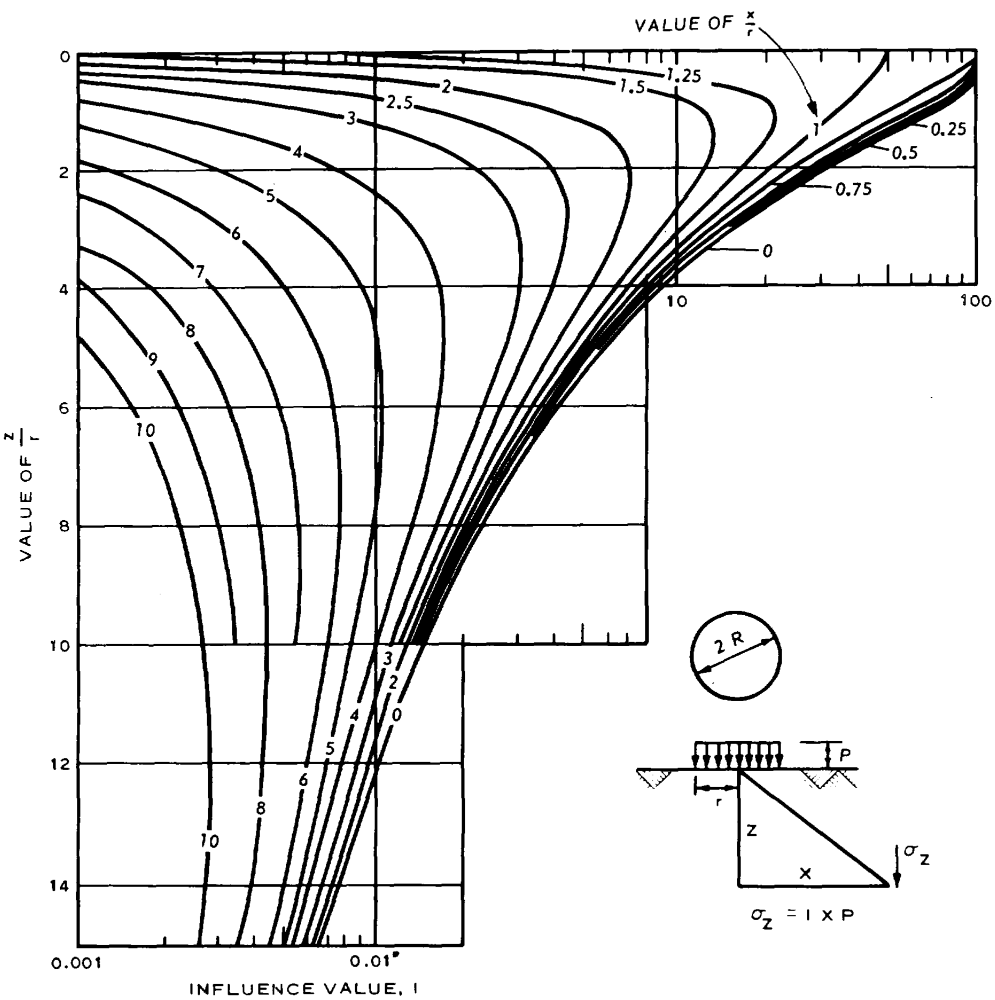


*Figure 5-3. Influence value for vertical stress under a uniformly loaded circular area.*

the pressure void ratio curve is fairly straight, it may be convenient to work with the compression index, in which case the formula for settlement is as follows:

$$\Delta H = \frac{C_c}{1 + e_0} H \log_{10} \frac{p_2'}{p_1'} \qquad (5\text{-}2)$$

An example of a settlement analysis in which the rebound of the foundation and subsequent recompression under the building load are determined is shown in figure 5-4 for a normally consolidated foundation.

*b. Rate of settlement.* The rate of settlement is determined by means of the theory of consolidation. This

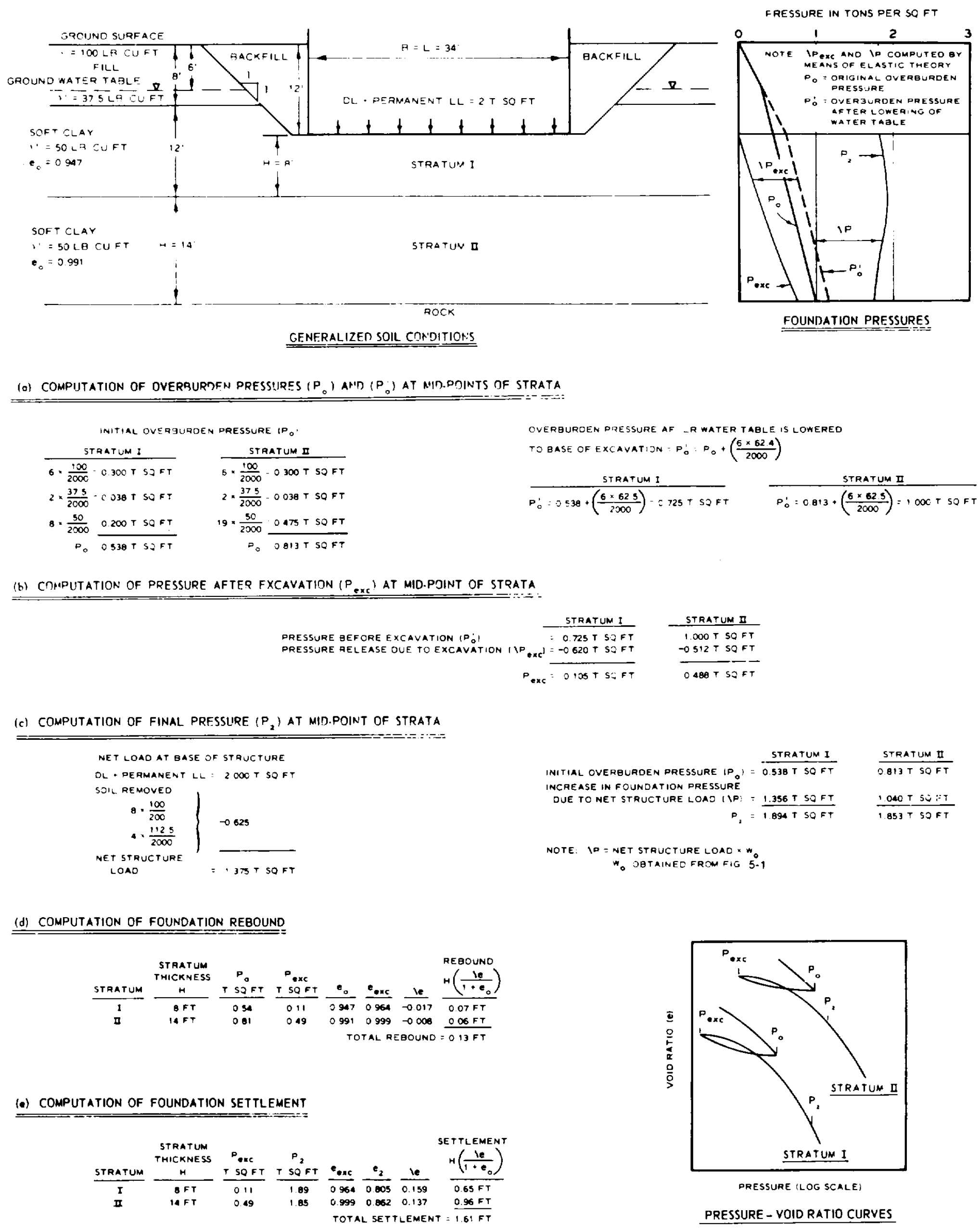


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*Figure 5-4. Example of settlement analysis.*

theory relates the degree of consolidation and time subsequent to loading according to the following expression:

$$U(\%) = f(T) \qquad (5\text{-}3)$$

with

$$T = \frac{c_v}{H^2} t \qquad (5\text{-}4)$$

where

- U = degree of consolidation or ratio of settlement that has occurred at a given time to the ultimate settlement
- T = dimensionless number called the time factor that depends upon loading and boundary conditions
- $c_v$ = property of the soil known as the coefficient of consolidation
- H = length of the drainage path, which in the case of a specimen or stratum draining from top and bottom would be half the thickness of the specimen or stratum
- t = time corresponding to U

The relation between time factor and percent consolidation for various boundary conditions is shown in figure 5-5. If the values of $c_v$ and H are known for a stratum of clay with given boundary conditions, the theoretical curve can be replotted in the form of a percent consolidation-time curve; if the ultimate settlement of the layer has been computed, the curve can be further modified into a settlement-time curve. In order to compute, $c_v$, it is necessary to transform the laboratory time-consolidation curve for the load increment in question into the theoretical curve. A method for ad- justing the laboratory curve in order to compute the

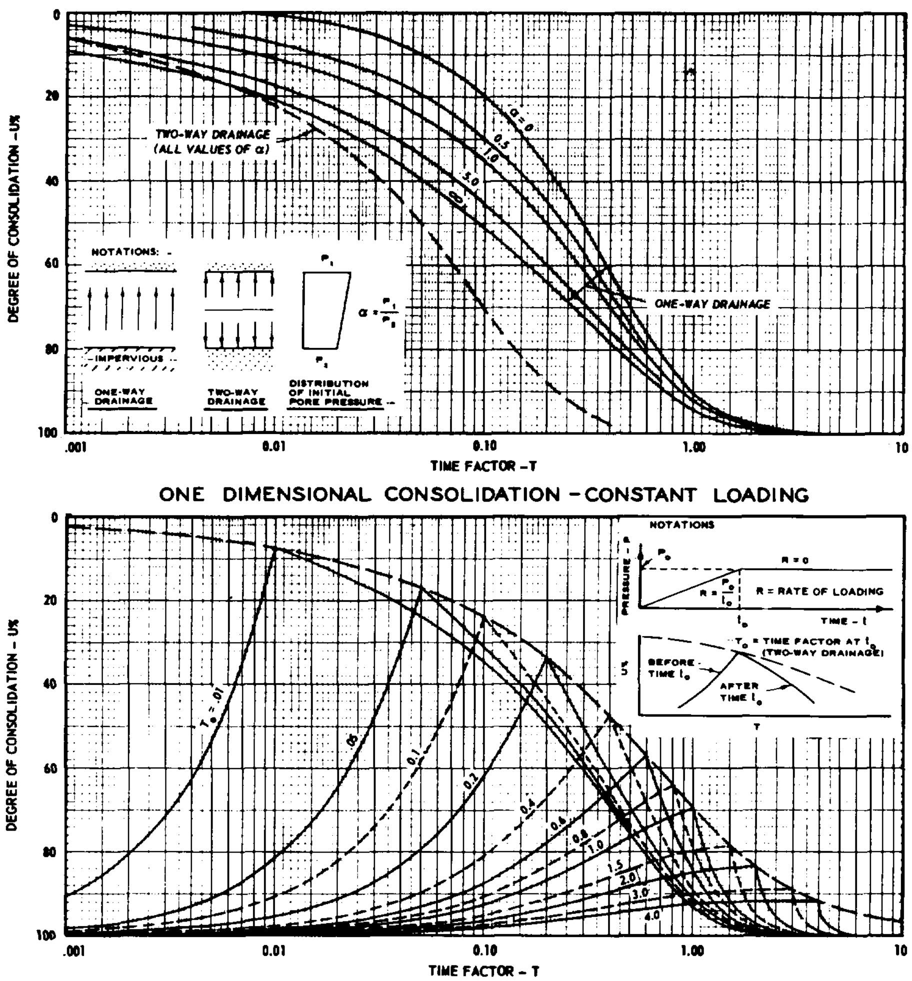


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*Figure 5-5. Time factors for various boundary conditions.*

coefficient of consolidation, $c_v$, is shown in figure 3-7. Thus, the actual time required for the various percentages of consolidation to occur in the field can be determined by the following formula:

$$t_f = \frac{T H^2}{c_v} \qquad (5\text{-}5)$$

where

$t_f$ = time for U(%) consolidation in the field stratum

H = length of the drainage path in the field

T = time factor corresponding to U(%) consolidation

When settlement occurring during the construction period may be of interest, the values of T and U also can be obtained from figure 5-5.

*c. Secondary compression.* For refined estimates and special purposes, settlement resulting from secondary compression may have to be evaluated. The amount $\Delta H_s$ can be calculated as follows:

$$\Delta H_s = C_\alpha H \log \frac{t_{sc}}{t_p} \qquad (5\text{-}6)$$

where

$t_{sc}$ = $t_p$ + time interval during which secondary compression settlement is to be calculated

$t_p$ = time to complete primary consolidation

H = total thickness of compressible soil

Other terms have been previously defined. Secondary compression settlements may be important where primary consolidation occurs rapidly, soils are highly plastic or organic, and allowable settlements are unusually small.

**5-6. Settlement of cohesionless soils.** The permeability of cohesionless soils is usually sufficiently great that consolidation takes place during the construction period. For important projects, estimate settlement using consolidation tests on undisturbed samples or samples remolded at natural density. Alternately, settlements may be estimated from plate bearing tests described in chapter 4. Design of footings on cohesionless soils, based on settlement considerations using the Standard Penetration Test, is described in chapter 10.

**5-7. Eliminating, reducing, or coping with settlement.** Design techniques for ameliorating settlement problems are summarized in table 5-4. Differential settlements beneath existing structures can be corrected by releveling by jacks, grouting (i.e., mud jacking) beneath slab foundations, or underpinning. These techniques are expensive, to varying degrees, and require specialists.

*Table 5-4. Methods of Eliminating, Reducing, or Coping With Settlements.*

| Method | Comment |
|---|---|
| Use of piles, piers, or deep footings. | Differential settlements between buildings and surrounding ground can cause problems. |
| Excavate soft soil and replace with clean granular fill. | Can be very costly if the compressible layer extends to large depth. |
| Displace soft soil with weight of granular fill or by blasting. | Difficult to control.Pockets of entrapped soft soil can cause large differential settlements. |
| Reduce net load by excavation. | Weight of one story building is equal to weight of one or two feet of soil. |
| Surcharge or preload site before construction. | Settlement is reduced by amount which occurs before construction. Preload may be limited by stability considerations. |
| Delay construction of buildings to be built on fills. | Settlement which occurs before construction does not affect building.Fill settlement can be accelerated using sand drains. |
| Use a stiff foundation with deep grade beams. | Can greatly reduce differential settlements. |
| Install leveling jacks between the foundation and the structure | Building can be releveled periodically as foundation settles. |
| Select a building type which has a large tolerance for differential settlement. | Steel frames, metal siding, and asphalt floors can withstand large settlements and remain serviceable. |

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